

MATERIAL SHIELDS AGAINST NEUTRAL ATOMIC PARTICLE BEAMS

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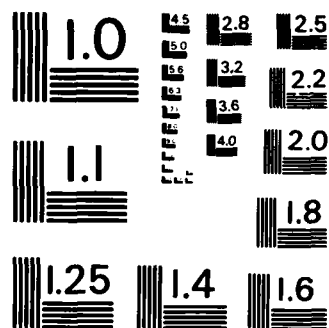
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Material Shields Against Neutral Atomic Particle Beams

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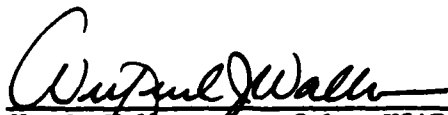
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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.


W. J. Walker, Lt. Col., USAF
Project Officer

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CONTENTS

1.	INTRODUCTION.....	5
2.	RANGE.....	7
3.	RANGE IN ELEMENTAL MATERIALS.....	9
4.	SELECTION OF SHIELD MATERIAL.....	17
5.	HEAVIER ATOMIC PARTICLES.....	21
6.	SECONDARY RADIATION.....	23
7.	CONCLUSION.....	25
	REFERENCES.....	27

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FIGURES

1.	Total Path Length and Extrapolated Range of Protons in Carbon.....	8
2.	Stopping Power for Several Elemental Materials.....	10
3.	Stopping Power for 100-MeV Protons in Elemental Materials.....	12
4.	Range of 10-MeV and 100-MeV Protons in Elemental Materials.....	13
5.	Range of Protons in Several Materials.....	15
6.	Range of Several Light Particles in Aluminum.....	22

TABLE

1.	Range of 100-MeV Protons in Various Materials.....	19
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1. INTRODUCTION

Atomic particle beams are under consideration for space-to-space weapons. In principle, an intense beam of atomic particles can seriously damage or degrade a satellite. At high-fluence levels the beam would be capable of producing structural damage to the satellite. At lower-fluence levels the beam would still be capable of damaging internal sensitive electronic components provided the individual particles in the beam were energetic enough to penetrate to the interior of the spacecraft.

Particle beams that have been proposed for space-to-space weapons application are generally conceived to consist of neutral atoms. If the particles were charged, the beam would suffer in at least two respects: repulsion between the charged particles would soon defocus the beam, and deflection of the charged particles by the earth's magnetic field would make it difficult to aim the beam. The beams are produced by accelerating a stream of ionized atoms and then neutralizing the atoms before they are ejected. The initial ionization is accomplished by adding electrons to a stream of neutral atoms (e.g., adding electrons to neutral H atoms to produce H^- ions). The extra electrons are subsequently stripped off by passing the negative ions through a thin shield or a few micrograms of gas before ejecting them.

Defense against a beam of energetic atomic particles can be provided by a material shield, an electric or magnetic field, or a combination of these.^{1,2} A material shield will absorb the energy of the beam and can be used whether the incident particles are neutral or electrically charged. Electromagnetic fields can be used to deflect the beam, but only if the particles in it are electrically charged.

For many shielding applications, materials made up of low atomic-number (Z) elements are preferred. Compounds of low-Z elements offer the following advantages: (1) their ranges in terms of per-unit-area mass are lower, (2) they produce far less secondary radiation, and (3) their specific heats are relatively high. Among the disadvantages of low-Z materials are typically low-density and low-temperature phase changes.

2. RANGE

Upon entering a material shield, a high-velocity atom will lose one or more of its electrons within a few interatomic distances. Thereafter, the energy of the resulting charged particle will be dissipated by interactions with the electrons and atomic nuclei in the shield.³ Most of the energy will be dissipated by multiple coulombic interactions with the electrons. This leads to the excitation and ionization of the atoms in the shield, to the induction of plasma oscillations in the conduction electron gas, and to the production of bremsstrahlung. The energized electrons will in turn produce additional ionization. At very high and very low particle energies, collisions with the atomic nuclei are important. At high energies (above about 100 MeV for protons), inelastic collisions with the nuclei will produce muons, neutrons, and other radiation that can be more penetrating than the original particle. At low energies, nuclear collisions and capture will quickly bring the particle to rest.

The net distance the incoming particle has traversed before being stopped or captured is called its range. The range is usually expressed in centimeters or, more often, in grams per square centimeter of stopping material along the path length. A typical range versus incident energy relation is illustrated in Figure 1.

The net distance a particle travels before its motion is arrested is generally somewhat less than the total distance it actually travels because of the small deflections it undergoes along the way as a result of interactions within the shield. Furthermore, the range will vary somewhat from particle to particle, particularly toward the end of the range where the particle motion is most erratic. Usually an extrapolated or average range is given as a function of particle incident energy. The variation in particle range (so-called straggling) becomes relatively less important as the incident energy increases; see Figure 1. For 100-MeV protons the straggling is less than two percent of the projected range. For heavier particles the straggling is even less.

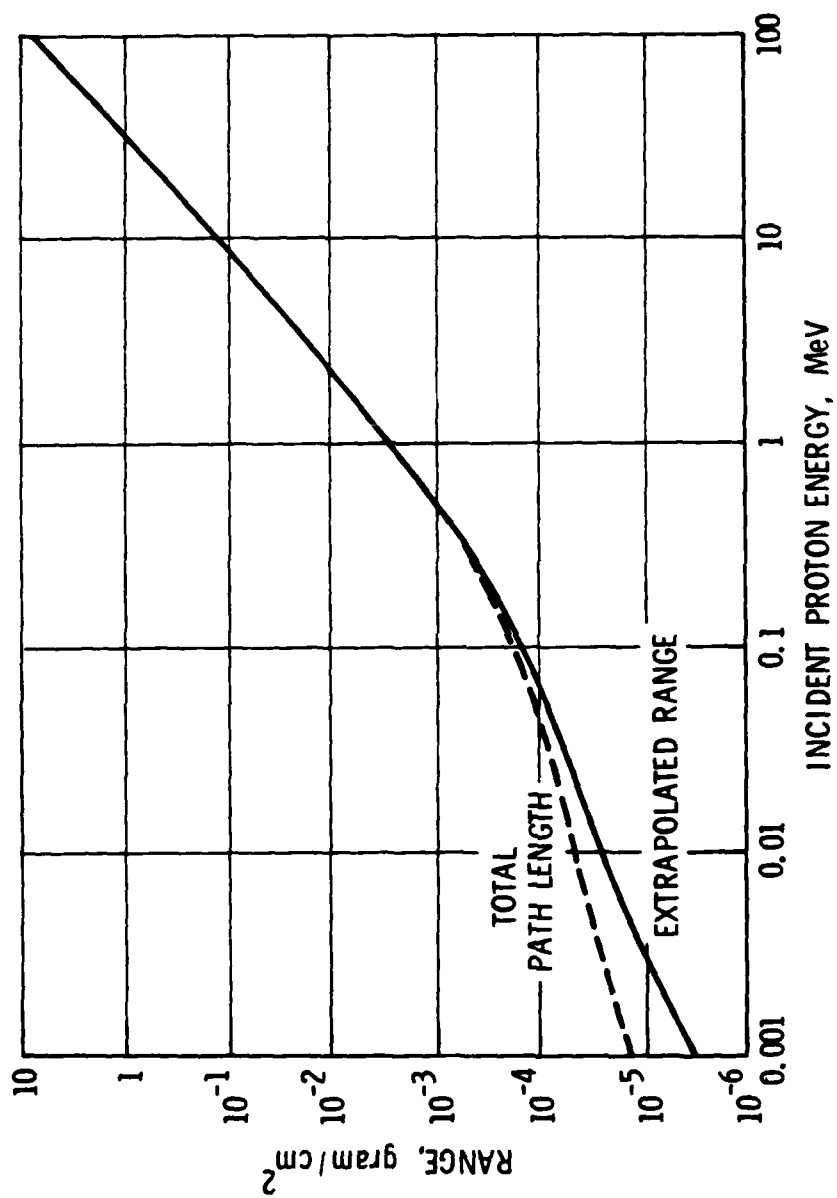


Figure 1. Total Path Length and Extrapolated Range of Protons in Carbon

3. RANGE IN ELEMENTAL MATERIALS

Over most of its range, the energy of an incident particle is dissipated through long-range coulombic collisions with the electrons surrounding the atomic nuclei of the shield. The fractional loss of energy per electron collision is small, but the energy is gradually reduced by numerous interactions. The so-called stopping power (SP) of a material is a measure of the particle energy loss while it traverses a unit distance in the material or a unit mass of material per unit area:

$$(SP) = -dE/dx \quad \text{or} \quad (SP) = -dE/\rho dx$$

where ρ is the material density. The stopping power is a function of the atomic number (Z), and the energy (E) of the particle. For example, a 100-MeV proton in aluminum, $_{13}\text{Al}$, will lose energy at the rate of about 1.5 MeV per mm or 5.7 MeV per gram/cm².⁴ For 10-MeV protons, the energy loss in aluminum is increased to 9.2 MeV per mm or 34 MeV per gram/cm².

The stopping power for several elementary materials is shown in Figure 2. The values are given in terms of MeV per atom/cm², but can be converted to MeV/cm or MeV per gm/cm² by multiplying the data for a given element by that element's atomic density (atoms/cm³) or number of atoms per gram, respectively. For protons and heavier particles most of the energy is lost through ionization, so SP is essentially a measure of the ion-pairs produced along the range.

If the energy scale (abscissa) were plotted linearly, the SP curves in Figure 2 would rise steeply before falling to zero at the origin. This indicates that the ionization deposited per unit of range is heaviest near the end of the range. It is important, therefore, that the particles be stopped entirely within the shield material if sensitive components behind the shield are to be protected.

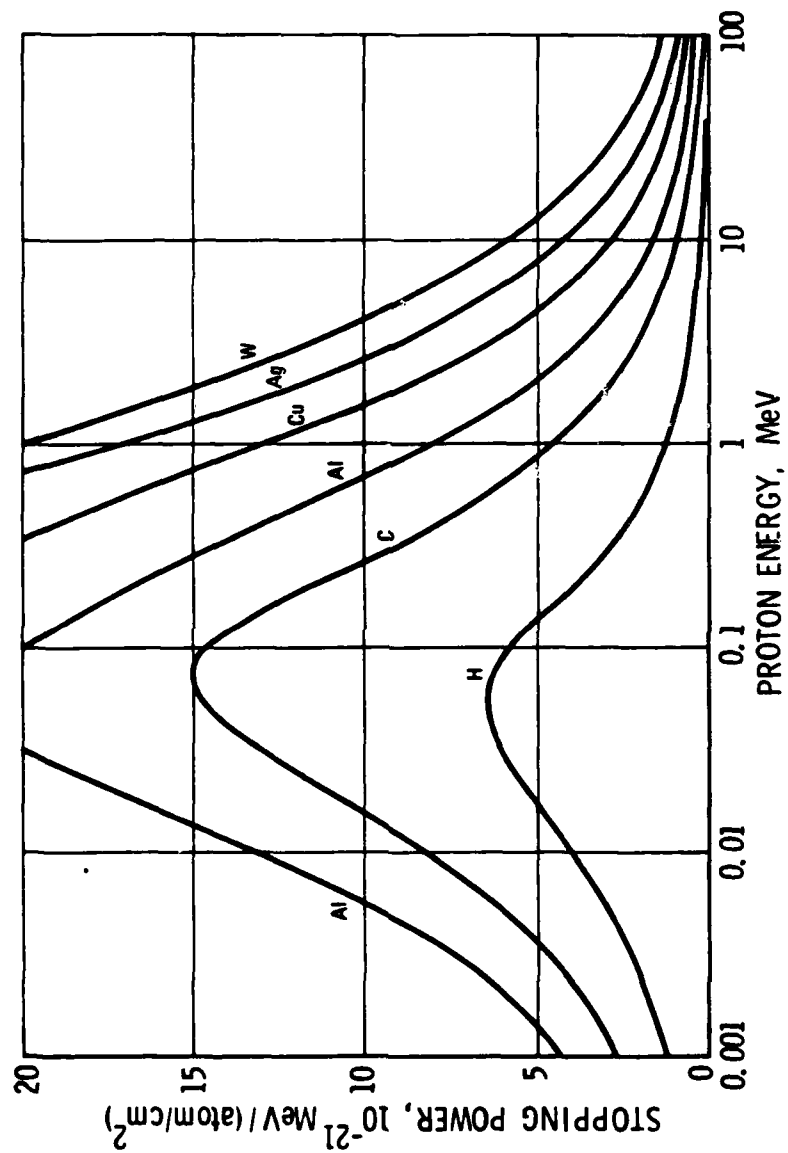


Figure 2. Stopping Power for Several Elemental Materials

Note that above 0.1 MeV the stopping power decreases with proton energy. Therefore, except at very low energies, the range increases faster than linearly with incident proton energy. From this standpoint, it is advantageous for the particle-beam weapon designer to strive for high particle energies. At relativistic energies well above those considered for particle-beam weapons the stopping power approaches a constant.³

The importance of the electrons in attenuating the proton energy is evident from the data shown in Figure 3, where SP for 100-MeV protons is plotted against the atomic number Z .⁴ The slope of the SP curve is near unity—actually about 0.9. Because the number of electrons per atom is proportional to Z , the stopping power (at least for large E) is roughly proportional to the number of electrons along the path of the proton.

Figure 3 also shows how the atomic weight (A) varies with Z . If the slope of A versus Z were equal to that of SP versus Z , the range (in grams/cm²) would be about the same for all elements. If the slope of A is greater, the range of protons should increase with the atomic number. Between Z equal about three (lithium) and ten (neon), the slopes are roughly equal. Above $Z = 10$, the slope of A versus Z (equal to about 1.1) is greater than that of SP versus Z . Accordingly, the range should be less in the low- Z materials, because these in essence provide more electrons per unit mass. In particular, we see that the range in hydrogen should be considerably less. Also, because A for carbon ($Z = 6$) is slightly below the local A versus Z curve, we would expect a small dip in the range for carbon in comparison with its atomic neighbors.

The above expectations are borne out in Figure 4, wherein range data for the elements are plotted (in grams per cm²) for two incident-proton energies. Note that the range for protons in elemental materials increases steadily as Z increases. The range in uranium is some 2 to 4 times the range in helium. At 100 MeV, the range in carbon is about 0.9 that of aluminum and only about 0.6 that of tungsten. Hydrogen is outstanding—its range is less than half that of helium.

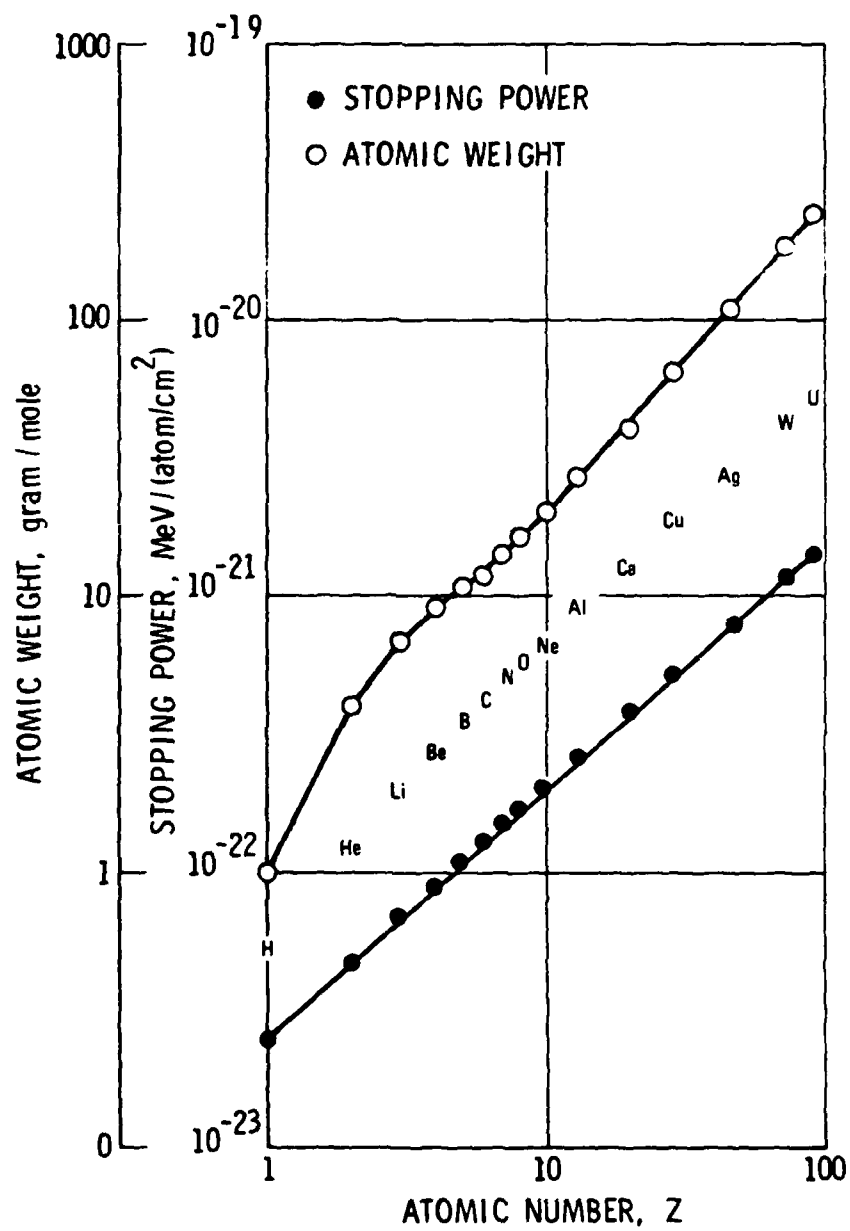


Figure 3. Stopping Power for 100-MeV Protons in Elemental Materials

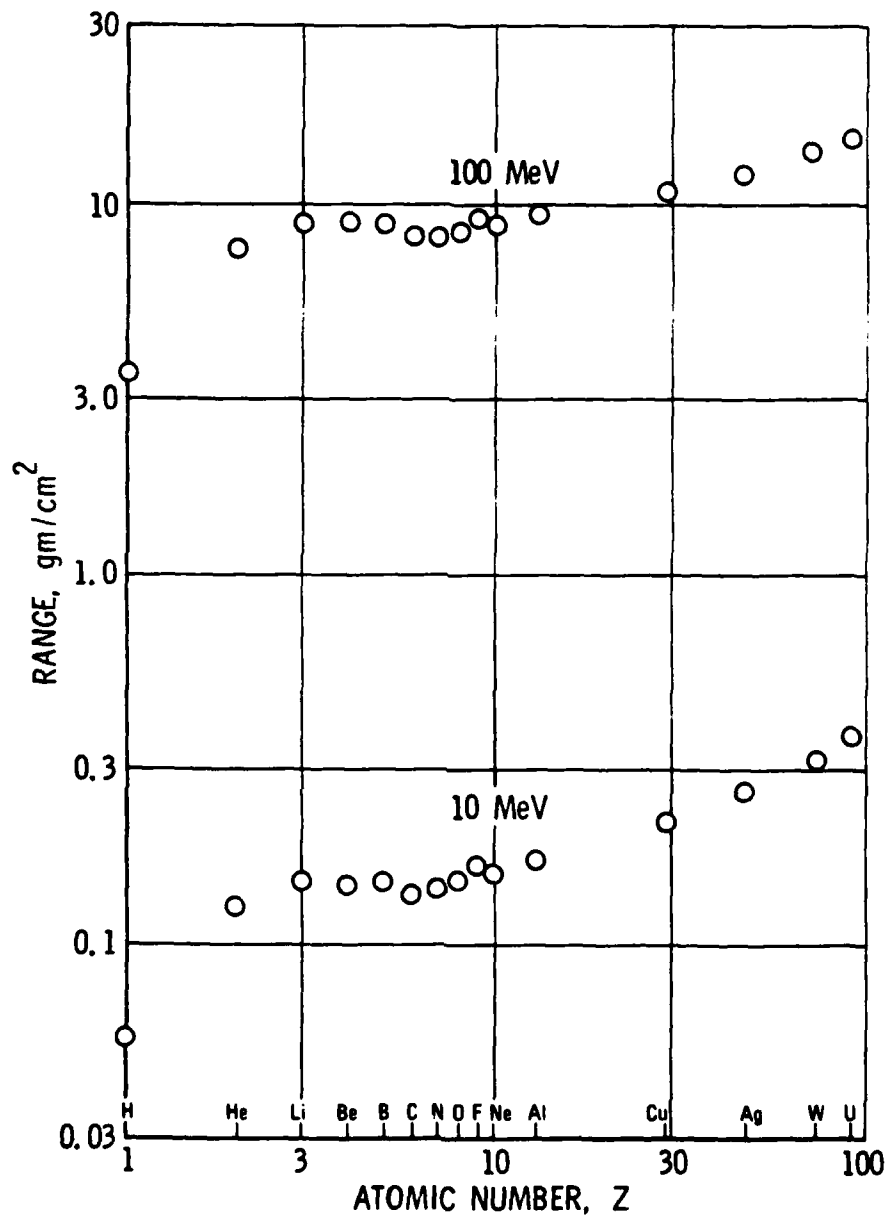


Figure 4. Range of 10-MeV and 100-MeV Protons in Elemental Materials

The proton range can be obtained by integrating SP over the energy interval from zero to incident energy

$$R = \int_0^{E_0} \frac{dE}{(SP)}$$

However, because the variation of the SP curves with energy is similar for all the stopping materials (compare with Figure 2), the inverse of the stopping power (at a specified energy) may be used to extrapolate the value of the range from one element to that of another. The higher the incident proton energy the more accurate is the extrapolation. The ranges shown in Figure 4 were obtained from Refs. 1 to 5, and are accurate to within a few percent; SP values from Ref. 3 were used to complete the curves at points for which explicit range data were missing.

As we have seen, electrons are the principal agents for slowing down the beam protons over most of the distance traversed by the protons. It follows that different atomic isotopes of a given element should be about equally effective (distance-wise) in dissipating the proton energy. On the other hand, if the range is expressed in grams/cm², we would expect a small but useful decrease in the range if the lighter isotope is used instead of the naturally occurring element material. For example, the isotope ${}^6_3\text{Li}$ (which comprises 7.4 percent of natural lithium) should provide a range reduction of about 13 percent; the isotope ${}^{10}_5\text{B}$ (which comprises 19.6 percent of natural boron) should provide a reduction of about 7 percent.

Proton range data for several materials are shown in Figure 5 as functions of incident proton energy. For each material the range increases approximately as the 1.75 power of the proton energy. Thus, the effectiveness of any material shield decreases severely as the beam-particle energy is raised.

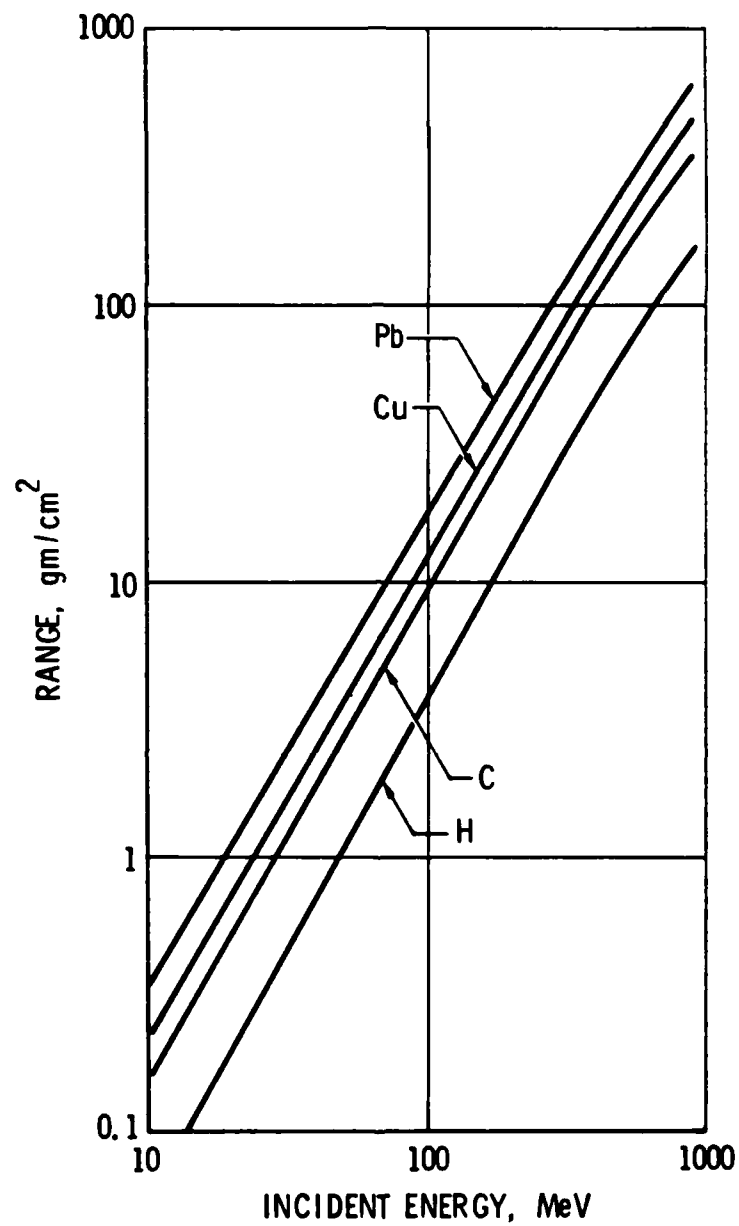


Figure 5. Range of Protons in Several Materials

4. SELECTION OF SHIELD MATERIAL

It has been shown that a particle-beam shield should be composed of low-Z materials, particularly hydrogen, if its weight is to be kept to a minimum. Of course, hydrogen by itself is not a very suitable shield material, because its use would require a cryogenic containment vessel, and its density is very low, even in a condensed state. However, hydrogen can be combined with other elements. One seeks a stable compound of low-Z elements with a high proportion of hydrogen. Carbon compounds look attractive because there are many hydrocarbon materials and carbon has a relatively small range for protons. There may also be suitable compounds between hydrogen and lithium or boron.

To determine the range of a composite material we utilize the Bragg rule, namely, that the stopping power of a compound is (within a percent or two) an additive function of the stopping powers of its constituent elements.^{6,7} Thus, as an example, we have for polyethylene, $(CH_2)_n$,

$$(SP)_{CH_2} = (SP)_C + 2(SP)_H$$

If we substitute the relationship discussed earlier between range and stopping power, namely,

$$R \propto A/(SP)$$

where A is the atomic weight, we obtain

$$R_{CH_2} = A_{CH_2} \cdot R_C R_H / (A_C R_H + 2A_H R_C)$$

Similar relationships can be developed for other compounds.

The ranges for 100-MeV protons in several elements and their compounds are given in Table 1. The ranges shown agree within a few percent with related values given in Ref. 7. The lighter isotopes of lithium and boron are used in the table. The listing is not exhaustive and there are probably other materials that may be suitable for a particle-beam shield. Clearly, the lighter-element compounds, particularly those rich in hydrogen, provide the lighter shield materials. They are bulkier, however, and in some ways may be less convenient to use. An aluminum shield would weigh about two-thirds that of a tungsten shield. Graphite, polyethylene, and lithium hydride would provide additional reductions in weight. Ammonia and methane, the lightest shield materials in the table would require cooling and containment. For very energetic beams, e.g., 1-GeV protons that require some 40 times as much shielding material as 100-MeV protons, serious consideration might be given to the use of ammonia or methane.

Table 1 shows how massive a material shield against particle beams would have to be. For example, a tungsten shield against 100-MeV protons would weigh about 29 lb/ft². By comparison, an equivalent polyethylene shield would weigh about 14 lb/ft². This comparison implies slab geometry, i.e., large targets. For small targets (i.e., those for which the radius is less than ten times the linear polyethylene range), account for the spherical aspect of the shield would offset somewhat the weight advantage of the bulkier polyethylene material.

Table 1. Range of 100-Mev Protons in Various Materials

Material*	Symbol	Mole Weight (grams)	Range** gm/cm ²	cm	Comments
Hydrogen	H	1.008	3.5	--	Contains 0.015% H ²
Carbon	C	12.011	8.2	3.0-5.0	Graphite form; 99% C ¹² , 1% C ¹³
Polyethylene	(CH ₂) _n	14.027	6.9	7.5	A number of plastics available
Methane	CH ₄	16.043	6.1	14.8	Melts at -182°C; boils at -161°C
Lithium	Li	6.015	8.9	19.3	Li ⁶ is 7.4% of natural element
Lithium hydride	LiH	7.023	7.3	10.1	White crystal; melts at 680°C
Nitrogen	N	14.007	8.3	10.3	Melts at -21°C; boils at -196°C
Ammonia	NH ₃	17.031	6.7	8.7	Melts at -78°C; boils at -33°C
Boron	B	10.013	8.2	3.7	B ¹⁰ is 19.6% of natural element
Lithium borohydride	LiBH ₄	20.060	6.6	10.8	Decomposes at 275°C
Aluminum	Al	26.98	9.4	3.5	100% Al ²⁷ ; melts at 660°C
Tungsten	W	183.85	14.3	0.74	Melts at 3410°C

*The lighter isotopes of lithium and boron were selected; the natural isotopic mix was used for the other elements.

**The range in cm is given for the condensed state of each material. To convert gm/cm² to lb/ft² multiply by 2.05.

5. HEAVIER ATOMIC PARTICLES

Atoms other than hydrogen (i.e., neutralized protons) have been proposed for beam weapons. Among these are deuterium, helium, lithium and other light atoms. For reasonable beam energies, these atoms are stripped of all of their electrons when they enter a shield material. The heavier particles are then stopped more readily than protons because they are traveling more slowly at a given energy and because they carry a greater charge. (The stopping power for a fast charged atom is proportional approximately to the square of its charge divided by the square of its velocity.⁶) Consequently, the range of heavier particles is considerably less than that of protons of the same incident energy. Figure 6 provides a comparison of the ranges for several light atoms in aluminum.³⁻⁵ For 100-MeV incident particles, the relative ranges for hydrogen, deuterium, tritium, helium and lithium are 1.00, 0.59, 0.42, 0.085 and 0.025, respectively.

From a weapon designer's point of view, a hydrogen beam offers the advantage of greater penetration. On the other hand, a deuterium beam can be used to generate neutrons and complicate the problems for the shield designer. Heavier particles also produce more ionization per unit mass of target.

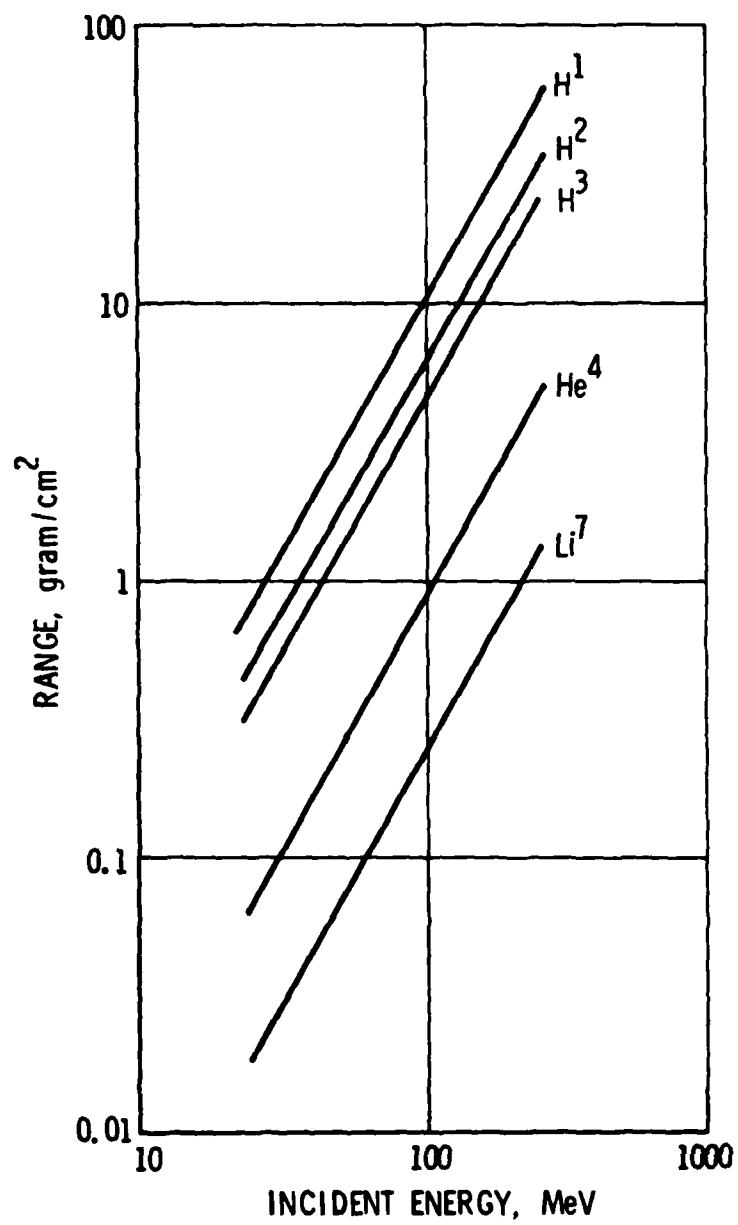


Figure 6. Range of Several Light Particles in Aluminum

6. SECONDARY RADIATION

Most of the energy of the incoming particle is dissipated by coulomb interactions with electrons. The losses are of two types: radiative loss through the production of bremsstrahlung, and loss through ionization and induction of plasma oscillations, i.e., through the production of secondary electrons. The probability of radiative loss is roughly proportional to

$$\frac{z^2 Z^2 E}{M_0^2}$$

where z is the particle charge (in units of electron charge), Z is the atomic number of the stopping material, and E and M_0 are the kinetic energy and rest mass of the particle, respectively.⁸ Thus, the production of bremsstrahlung is proportional to the energy of the particle and the square of the stopping material atomic number.

The ratio of the energy lost by bremsstrahlung production to that lost by secondary-electron production is approximately

$$r = \left[\frac{m_0}{M_0} \right]^2 \frac{ZE}{1600 m_0 c^2}$$

where m_0 is the rest mass of the electron and c is the velocity of light. For 100-MeV protons, the ratio is

$$r = 3.7 \times 10^{-8} Z.$$

Thus, the fraction of the energy converted to bremsstrahlung is

$$f = r/(1 + r) \approx r$$

and the bremsstrahlung energy (in MeV) per 100-MeV proton is

$$3.7 \times 10^{-6} Z.$$

For a carbon or tungsten stopping material, the energy converted to bremsstrahlung is, respectively, about 0.022 and 0.27 keV per 100-MeV proton. For heavier particles of the same incident energy, the bremsstrahlung energy will be reduced in proportion to the square of the particle mass.

It has been estimated that approximately 100 eV are dissipated in each primary ionization event and that each event results in the production of, on the average, three ion pairs, each consisting of a free electron and a positive ion. Some 20 to 40 eV are required to produce an electron-ion pair.⁸ The secondary electrons have a short range and contribute to local heating of the shield material. The bremsstrahlung are generally more penetrating, so it might be advantageous to add a thin layer of a high-Z material (e.g., Pb or W) behind the low-Z shield to provide added protection for internal electronic components.

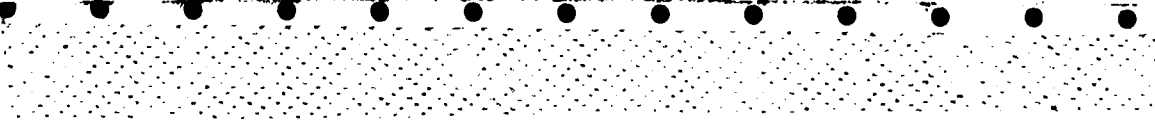
7. CONCLUSION

The range of protons and other light ions in elementary materials and a number of light-element compounds has been examined. The range is greatest for a beam of high-energy protons. Light-element compounds, rich in hydrogen, provide the lightest shield materials against atomic particle beams. These compounds are, however, bulkier than metallic shields and, except for carbon, have much lower phase-change temperatures. On the other hand, the light-element compounds have greater specific heats than the metals and also produce less secondary (bremsstrahlung) x-radiation. If a shield is to be used to provide protection against a neutral particle beam, it should be thick enough to completely stop the atomic particles and their secondary radiation.

Material shields against neutral particle beams can be quite massive. For example, a ten-foot diameter polyethylene shield against 100-MeV protons would weigh about 1100 lb, which might be acceptable. Against 300-MeV protons, the shield weight would jump to about 7600 lb, which may be a bit heavy.

For protection against very-high-energy particle beams, methods other than material shielding should also be considered. One suggested method would involve a very thin shield, placed at a large distance from the target, so as to ionize the beam and lessen its impact on the target by initiating defocusing and deflection. Another method proposed would involve the erection of a large screen or balloon to obscure the position of the target and complicate the aiming of the particle beam. Once inflated, an obscuration balloon will maintain its shape for a long time, even if punctured.

REFERENCES

1. S. Kash and R. Tooper, "Active Shielding for Manned Spacecraft," Astronautics (September 1962 and January 1963).
2. S. Kash, "Minimum Structural Mass for a Magnetic Radiation Shield," AIAA Journal (June 1963).
3. E. Condon and H. Odishaw, eds., Handbook of Physics, Second Edition, McGraw-Hill Book Co. (1967).
4. H. Anderson and J. Ziegler, Hydrogen--Stopping Powers and Ranges, Pergamon Press (1977).
5. 
6. D. Gray, ed., American Institute of Physics Handbook, Second Edition, McGraw Book Co. (1963).
7. J. Janni, Calculations of Energy Loss, Range, Pathlength, Straggling, Multiple Scattering, and the Probability of Inelastic Nuclear Collisions For 0.1- to 1000-MeV Protons, Air Force Weapons Laboratory, AFWL-TR-65-150 (September 1966).
8. R. Besancon, ed., Encyclopedia of Physics, Reinhold Publishing Corp. (1966).

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